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# Magneto-Rheological Fluid Semiactive Suspension System Performance Testing on a Stryker Vehicle


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## ABSTRACT

A Magneto-Rheological (MR) Fluid Semiactive Suspension System was tested on a Stryker vehicle, Infantry Carrier Variant (ICV), to determine the performance improvements compared to a standard ICV Stryker vehicle. In January 2005, the testing was conducted at the U.S. Army Yuma Proving Grounds located in Yuma, Arizona. The testing was conducted under the guidance of the U.S. Army Tank-Automotive Research, Development, and Engineering Center (TARDEC) of Warren, Michigan and MillenWorks of Tustin, California. The core of the system tested is comprised of 8 dampers and controllers using proprietary algorithms to modulate individual wheel forces in response to terrain inputs and body motion. Functionality of the Standard Stryker vehicle's pressurized gas spring and ride height management system was fully retained while maintaining the physical envelope of the original damper. The systems low power consumption (80 watts idle, estimated 250 watts cross-country, and 800 watts theoretical peak) did not require an additional power source. The MR Suspension system was intentionally designed to maintain the standard wheel travel, spring rate, and spring gas volume.

Over a range of off-road bump courses, the MR Stryker's best performance was a 72% increase in the vehicle's speed, from 22 mph (standard vehicle) to 38 mph at the 6-watt level of driver absorbed power (a measure of transmitted vibration). The system also showed marked improvements during aggressive on-road maneuvers like lane changes. The rate of vehicle roll was reduced by 30%. The maximum lane change speed increased from 38 mph (standard vehicle) to over 50 mph with the MR system.

This suspension technology is a cost effective, bolt-on system that has increased cross-country speeds, improved ride quality, and helped with platform stability thereby increasing battlefield effectiveness, safety levels for the operator and crew, and reducing potential for vehicle damage and associated maintenance activities. Its relatively simple design and cost effectiveness allows insertion of this technology into new vehicle designs, both wheel and track, as well as the potential for spiral upgrades with existing vehicles.

## INTRODUCTION

This report documents the testing of the magneto-rheological fluid semiactive suspension system on a Stryker vehicle as shown in Figure 1. The vehicle modifications and testing were conducted under a Small Business Innovative Research contract (SBIR) with MillenWorks. Under this SBIR, MillenWorks designed, fabricated, and installed the modified struts and control system on the Stryker. TARDEC then sponsored the formal mobility testing at Yuma Proving Grounds (YPG) in Yuma, Arizona.

Figure 1 – Stryker Infantry Carrier Vehicle

The MR Fluid Suspension system was developed by MillenWorks through 5 years of Small Business Innovative Research (SBIR) contracts. Under the first phase of the SBIR contract, MillenWorks investigated available MR fluids and a variety of damper design approaches based on such fluids. A commercially

available MR fluid was selected and MillenWorks designed and laboratory tested a prototype MR fluid based shock absorber. The successful laboratory testing of this unit led to the SBIR Phase 2 contract which was to develop, fabricate, install, and test a complete system on a High Multi-Mobility Wheeled Vehicle (HMMWV). The results of the HMMWV demonstration proved that the technology was viable for a light weight vehicle. The next step was to determine if this system was scalable by applying it to a vehicle of a larger weight class. This led to the Phase 2 Plus contract which was to develop, fabricate, install and test an MR system on a 20 ton vehicle.

The purpose of the Phase 2 Plus contract was to develop a complete MR fluid based, semiactive suspension system for application on a Stryker. The complete semiactive system would include the MR fluid based actuators, all required vehicle state sensors, the vehicle controller, and all necessary electrical interface components. The system was to be designed, developed, and installed on an ICV Stryker by MillenWorks. Evaluation and testing of the completed MR Stryker was to be funded and carried out by the US Army at Yuma Proving Grounds in Yuma, Arizona. The purpose of the Phase 2 Plus effort was to optimize the cross-country ride of the resulting semiactive suspension vehicle while also improving the vehicle stability and handling. The measure of success of the program was to be in terms of the amount of improvement in cross-country ride and on road handling that the MR Stryker exhibited over the Standard Stryker.

MillenWorks was selected for their participation in this program based upon their experience and success in designing high performance off-road vehicles and suspension systems. They utilized a commercially available MR fluid and designed and fabricated their own MR fluid shock absorber and semiactive suspension system.

The following sections discuss briefly the past semiactive suspension efforts at TARDEC and the MR fluid based semiactive suspension developed and tested on the HMMWV. This is followed by a description of the test and evaluation plan and the subsequent test results for this MR Stryker and the Standard Stryker as carried out at YPG in January 2005.

## SEMIACTIVE SUSPENSION PAST RESULTS

The US Army has been investigating the incorporation of semiactive suspension systems in its combat vehicle designs for the last decade. Semiactive suspension, also sometimes referred to as adaptive or active damping, is a system that rapidly modulates the damping force of each shock absorber to improve vehicle ride and stability. A variety of vehicle motion sensors can be used as input to the semiactive suspension controller to permit the judicious use of available vehicle damping forces. The sensors used may include chassis and wheel vertical accelerometers, chassis pitch and roll rate sensors, a steering angle sensor, and suspension travel and/or rate sensors.

A semiactive suspension requires virtually no additional power from the vehicle to vary the vehicle damping. All that is required (in addition to the controller power) is to switch the damping force rapidly between different values. The relative motion across each suspension member can only be resisted by that wheel's damper. In other words, for the semiactive suspension, the only control option is in terms of whether or not to resist the relative motion (and how strongly). The power required to resist the relative motion is lost as heat (as in a standard damper). Active suspension, in contrast, can enhance or oppose suspension relative motion, and therefore requires additional power from the vehicle to provide the control force (although in the resisting mode this could be done with a controllable damper as in the semiactive case).

The results of each of TARDEC's semiactive suspensions have been quite positive. A 22 ton experimental tracked vehicle (called the Mobility Technology Test Bed or MTTB by its creator) was tested over a variety of cross-country terrains. Five different configurations of the semiactive MTTB were tested against its equivalent normally damped system [1]. A 30-40% increase in cross-country ride limiting speed (as measured by driver's absorbed power) was recorded for each of the five vehicle configuration pairs.

Spurred on by the significant success of the semiactive suspension on the MTTB, the M1A1 and the M2 (i.e. the Abrams and the Bradley) vehicles were then modeled with semiactive suspension systems [2]. The simulations of these vehicle concepts demonstrated a similar percentage performance gain over the standard vehicles for most of the cross-country terrains. At the very rough terrain (the 3.5 inch rms), however, the improvement was a bit less.

Following the simulation study, an M2 Bradley vehicle was subsequently modified to include a semiactive suspension system. The semiactive damping was incorporated into an existing in-arm hydropneumatic suspension system and installed on a Bradley vehicle. This vehicle also underwent a thorough set of performance tests along with a standard Bradley [3]. The semiactive Bradley again showed about a 30 % increase in ride limiting speed over the standard Bradley over a wide variety of cross-country terrain profiles.

The MTTB employed hydraulic damping with a computer controlled damping orifice to achieve its variable damping. The Bradley system, on the other hand, used a set of friction discs to supply the damping force. The normal force applied to the friction discs was controlled through a small hydraulic actuator.

In the 1993-94 time period, an experimental controllable shock absorber using an electrorheological (ER) fluid was also developed and demonstrated in the laboratory [4]. The ER shock absorber had an unacceptable size to force ratio and the fluid experienced significant settling problems.

The capabilities and advances of magnetorheological (MR) fluids came to light in the mid 90s and made an MR fluid damper seem more practical than its ER counterpart. Thus an effort to develop and demonstrate a MR fluid based semiactive suspension system on a HMMWV was initiated in 1999 leading to the development and demonstration of an MR fluid based semiactive suspension system on a Stryker. This paper reports the performance results obtained from this development effort.

## MR FLUID SEMIACTIVE SUSPENSION

A MR fluid is a material that responds to an applied magnetic field with a significant change in its rheological behavior [5]. The properties of such a fluid can change from a free-flowing, low viscosity fluid, to a near solid when a magnetic field is applied. The change in properties takes place in a few milliseconds and is fully reversible. The yield strength is controllable by the strength of the magnetic field.

A typical MR fluid contains microscopic iron particles (typically 3-5 microns) which attributes to about 20-40% of its volume. These particles are suspended in a carrier fluid such as water, mineral oil, or synthetic oil. The resulting fluid can be as much as 80% iron by weight. Various additives are incorporated in the MR fluid to improve lubricity, reduce wear, and improve the suspension of the iron particles in the fluid.

MR fluid shock absorbers have been used as adjustable linear shocks in on-road racing applications for several years and have also found commercial application in heavy truck seat suspensions and in washing machines. More recently, a MR fluid based semiactive suspension system has been developed and marketed by Delphi Automotive [6]. This system is called the MagneRide system and it consists of four MR fluid based actuators, sensors, and a controller. This MR fluid based semiactive suspension is available on the Cadillac and Corvette models.

The following sections describe the test and evaluation plan and the subsequent test results for this MR Stryker and the Standard Stryker as carried out at Yuma Proving Grounds (YPG) in January 2005.

## TEST PLAN

The U.S. Army Tank-automotive Research and Development Center has long been involved in the development and evaluation of advanced suspension technologies. The major focus of these efforts is to increase the cross-country mobility performance of combat vehicles while not degrading the vehicle's stability and maneuverability. The objective of this formal testing was to quantify the relative performance in terms of ride quality, shock response, and maneuverability, of the magneto-rheological fluid (MR) semi-active suspension on the ICV Stryker, with respect to that of the standard ICV Stryker with a passive suspension system.

## RIDE QUALITY

The performance criterion for ride quality is based on absorbed power. Absorbed power is a measure of a human's tolerance to vibration. The absorbed power theory was developed, tested, and quantified in the late 1960's at TACOM and is recorded by references [7-10]. Absorbed power is a time average of frequency weighted root-mean-square (rms) accelerations. The recognized ride limiting absorbed power for an average driver was determined to be approximately 6 watts for a medium short duration (maybe 3-10 minutes) [7-10].

For this program three separate ride quality courses were used at YPG. These courses are labeled as RMS courses 3, 4, and 5. The courses are hard packed gravel and are maintained and periodically resurveyed by YPG to maintain their roughness content. The courses initially had values of 1.5, 2.0, and 3.4 inches rms when they were built by Waterways Experimental Station. The courses were recently surveyed by Aberdeen Proving Grounds revealing the latest RMS values of 1.1, 1.7, and 3.3. A photograph of RMS 5 is shown in Figure 2.


Figure 2 - Terrain RMS Course 5 at YPG

Each vehicle (the MR Stryker and the standard Stryker) was run over a course at as near a constant speed as possible. The vertical acceleration was recorded at the base of the driver's seat and directly below the driver's torso. This vertical acceleration was then used to compute the driver's vertical absorbed power for that speed over that course. Generally the course was run in both directions at the same speed and the two drivers' absorbed powers were averaged. (Note that the absorbed power theory includes input for the driver's pitch and roll motion's and for the driver's feet. The criterion most generally used, however, employs only the driver's vertical absorbed power.) The vehicle speed is gradually increased on subsequent runs down the course to provide an accurate estimate of the vehicle driver's ride limiting speed on that course (i.e. the speed at which the driver received 6 watts of vertical absorbed power). This procedure is completed for courses with a variety of roughness levels and the ride limiting speed is plotted as a function of surface roughness.

## SHOCK QUALITY

The vehicle's shock transmission performance is based on the peak vertical acceleration measured at the base of the driver's seat. The driver's acceleration is measured over a series of rigid half-round obstacles of increasing height. The course is a concrete surface with the appropriate half round obstacle bolted in place on the course. Each obstacle is traversed at increased vehicle speeds until the driver's shock limit is exceeded. The driver's shock limit is set at 2.5 g's, and the speed at which he experiences this 2.5 g limit is recorded for each obstacle. A plot of the 2.5 g shock limiting speed versus half-round obstacle height is then used to quantify the vehicle's shock performance.

## MANEUVERABILITY

Maneuverability is defined here as the ability to safely execute various turning requirements at reasonable speeds. The maneuvers that are used to evaluate the maneuverability are the lane change and the slalom courses. The performance on these courses is measured in terms of the vehicle's roll motion and lateral acceleration as a function of vehicle velocity. A specific limit is not ascribed to these vehicle performance measures, but the relative performance between the MR Stryker and the standard Stryker can be made from the resulting data. The vehicle is driven through the courses at a constant speed (as near as possible) and the roll and lateral motions are recorded (as well as the steering input). The minimum and maximum values of roll rate and lateral acceleration are recorded for each vehicle speed that is run. This is done for both vehicle configurations and the results are plotted as a function of vehicle velocity.

## VEHICLE SETUP AND INSTRUMENTATION

The magneto-rheological fluid semi-active suspension system was installed by MillenWorks on an Infantry Carrier Variant Stryker. Ballast was added to both of the vehicles to give them each approximately the same total weight. The MR Stryker had a GVW of 40,750 lbs. whereas the standard Stryker had a GVW of 40,700 lbs. Figures 4 and 5 represent the individual wheel loadings for the vehicle as well as the GVW and tire pressures. The weight discrepancy between the two vehicles was noted, but was not considered a hindrance in the comparison of the two vehicles.

The standard Stryker, supplied by YPG, for comparison testing was an Infantry Carrier Variant with a serial number of 14. The MR Stryker was an Infantry Carrier Variant with a serial number of 234.

Figure 3 – String Potentiometer at each Wheel Station

Yuma Proving Grounds instrumented and performed the data collection for both the standard Stryker and the MR Stryker. Figure 3 illustrates the string encoders that were used to determine wheel position.

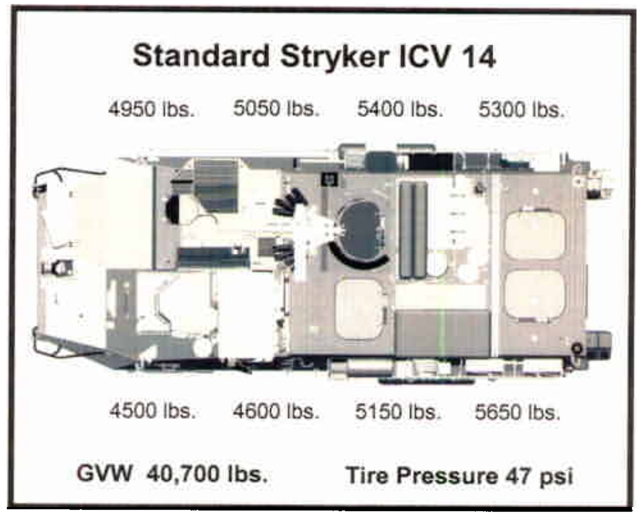


Figure 4 – Standard Stryker Loads

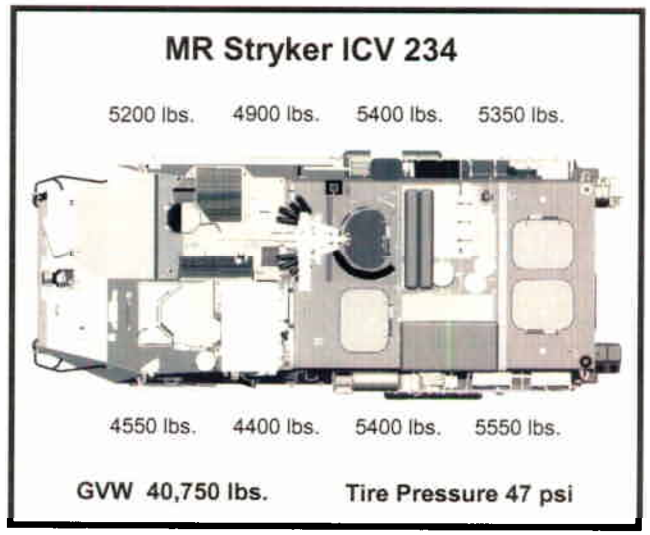


Figure 5 – MR Stryker Loads

The three angular rates and linear accelerations were recorded at approximately the cg of the chassis. A vertical accelerometer was mounted on the spindle of each wheel on the left side of the vehicle to assess wheel accelerations and a string potentiometer was mounted at each wheel station on the left side of the vehicle to measure suspension travel. Wheel and suspension measurements were taken on the left side of the vehicle only to reduce the number of sensors that would have to be monitored and the amount of data that would have to be collected from the vehicles. It was assumed that the performance of each wheel station would be symmetrical on both sides of the vehicle, therefore, the results taken from a wheel position on the left side of the vehicle represents the same wheel station on the right side of the vehicle. A separate vertical accelerometer was also mounted at the driver's seat to be used in driver's shock and ride quality performance measurement. And finally a steering angle sensor and a vehicle speed sensor were included. The MR Stryker vehicle also had sensors that measured the suspension

velocity with string encoders, the temperature of each strut, and an accelerometer was located in each control box. The controller for the MR Stryker Suspension collects data at a rate of 2000 Hz.

The standard Stryker and the MR Stryker were both instrumented identically to record all pertinent data. The data was collected with a Campbell Scientific RC9000 data acquisition unit at a rate of 500 samples per second. Exact instrument locations and ranges were determined in coordination between YTC and U.S. Army – TARDEC personnel. [11]

## TEST PROGRAM

The testing was conducted at Yuma Proving Grounds (YPG) during the week of January 10-13, and 21, 2005. The test program utilized two professional test drivers from YPG and generally alternated vehicles and drivers in the test sequence. The first testing that was completed was ride quality using the RMS courses. Many of the runs had to be repeated over the first three days due to some sensor failures, a hardware problem with a coil in a strut, and a programming problem with the controller. The fourth day of testing was the maneuverability testing which consists of the lane change and slalom courses. The shock quality testing, which is the half round testing, was completed on the last day. The shock quality test is usually performed last due to the harshness of the test and the possible damage that can be incurred.

The standard Stryker that was used for comparison testing was provided by YPG. The restrictions in using this vehicle included the limited amount of abuse we could inflict upon the vehicle. The maximum speeds that were allowed on RMS courses 3, 4, and 5 were 40 mph, 30mph, and 10mph. The maximum speeds that were allowed on the half rounds courses 8 inch, 10 inch, and 12 inch were 30 mph, 20 mph, and 10 mph.

## RESULTS

Comparisons between the two vehicles are described in graphical form in the following sections. The vertical accelerometer located on driver's seat was used to calculate the driver's vertical absorbed power values which are used as the basis for the ride quality curves described below.

### RIDE QUALITY PERFORMANCE

Three separate ride quality courses were exercised for this portion of the testing. These YPG courses are labeled RMS3, RMS4, and RMS5 and have surface roughness levels of 1.1, 1.7, and 3.3 inches root-mean-square (rms), respectively. The courses are measured in both the north and south direction with the average being the respective values. These ride quality courses are predominately pitch-plane courses (i.e. they do not induce vehicle roll motion). In the following plots the average of the two directions (north or south) at each speed is reported.

The vertical wheel accelerations that might typically be seen in cross-country operation were measured. Each vehicle had a vertical accelerometer mounted on the spindle of each wheel. Figures 6-8 compares the maximum and minimum vertical wheel accelerations at the left front wheel for each of the test vehicles over the RMS courses.

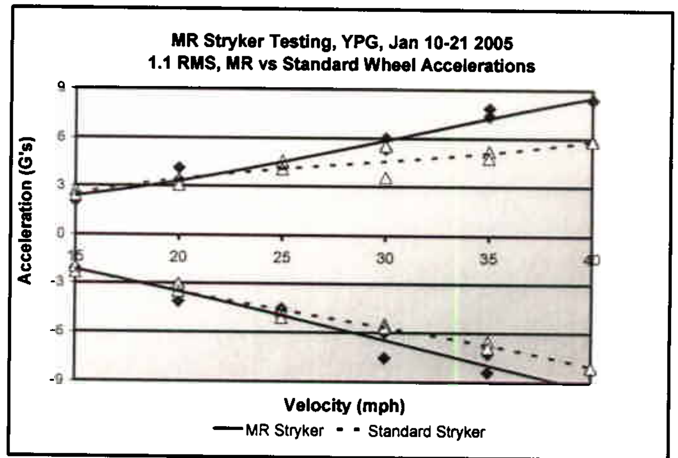


Figure 6- Comparison of Wheel Accelerations (1.1" RMS)

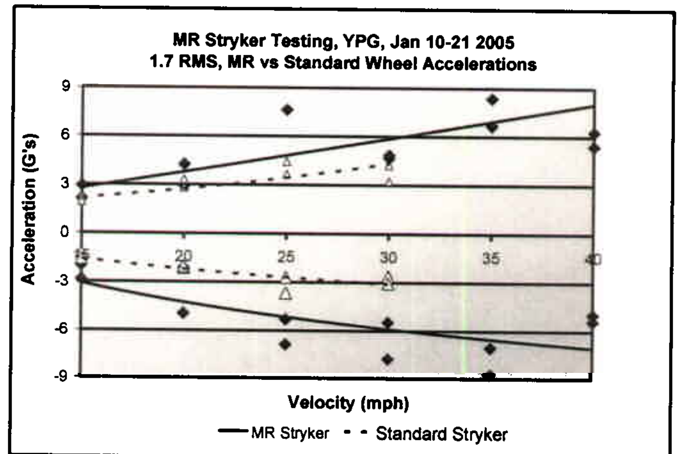


Figure 7- Comparison of Wheel Accelerations (1.7" RMS)

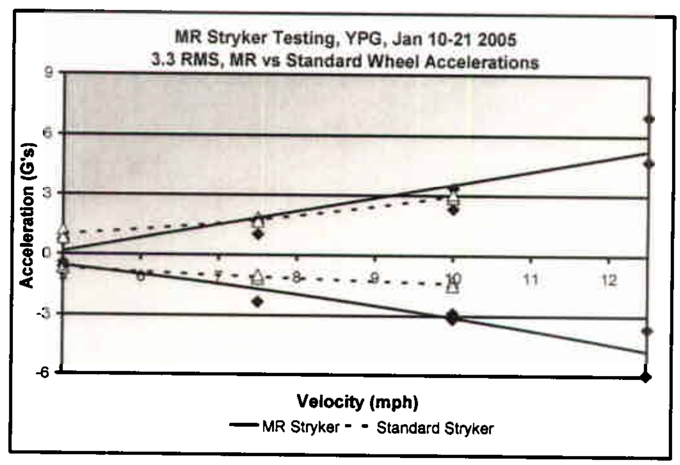


Figure 8 - Comparison of Wheel Accelerations (3.3" RMS)

Each figure contains the acceleration data as a function of vehicle speed for both vehicle concepts over one of the three RMS courses.

Suspension excursion, which will be referred to as suspension travel, was also recorded for both vehicles over each of the RMS courses. Since the courses were

not designed to induce vehicle roll, the wheel travel was analyzed only for the left side of the vehicles. Figures 9-12 show the minimum and maximum wheel travel experienced for the MR Stryker and the standard Stryker over the 1.1" and 1.7" RMS course (the 3.4" course had a very limited number of runs on it and is not shown here). The maximum suspension travel was recorded for each run and the difference between the north and south runs are recorded as the total wheel travel on these plots.

A close look at the wheel travel results over these rough cross-country courses reveals a couple of interesting features. First it should be noted that the standard Stryker and the MR Stryker have identical spring rates and wheel travel. The main suspension components (the upper stanchion tube and lower slider) used in the MR system are the standard components with some modifications to fit in the MR damper. The MR suspension system was designed intentionally to maintain the same physical wheel travel, spring rate and gas volume.

The wheel travel for the front wheel is 13.1 inches (333 mm) and the travel for the rear wheel is 13.37 inches (340 mm) respectively. These values do not take into account the foam rubber bump stops that may limit the bump travel, or the progression of the gas springs which would get really stiff close to full bump. The MR system used the same rubber bump stops and had the same gas volume as the standard system so there is no difference in suspension travel between the two systems.

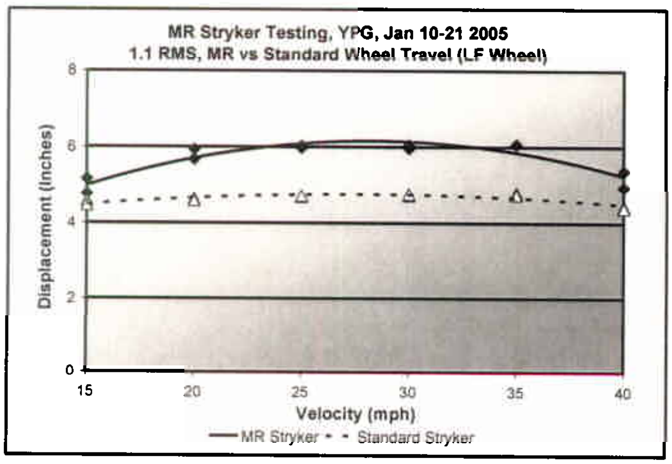


Figure 9 – Left Front Wheel Travel (1.1" RMS)

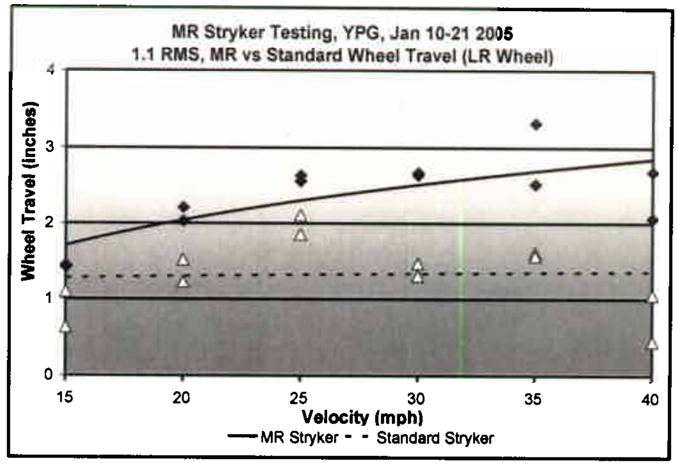


Figure 10 – Left Rear Wheel Travel (1.1" RMS)

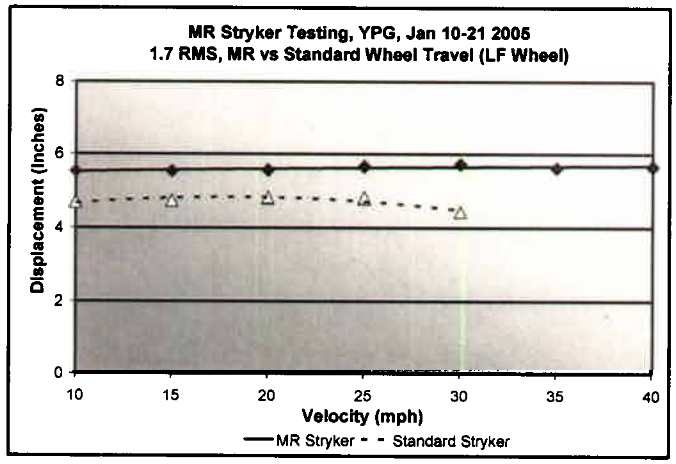


Figure 11 – Left Front Wheel Travel (1.7" RMS)

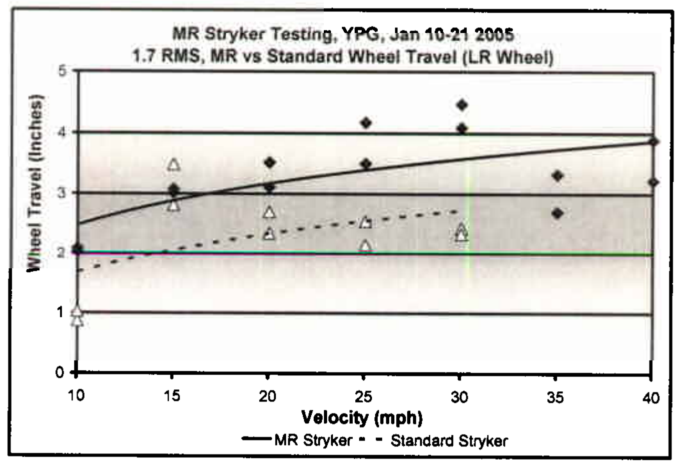


Figure 12 – Left Rear Wheel Travel (1.7" RMS)

The peak driver's vertical accelerations are shown in Figures 13-15. The driver's seat is near the front of the vehicle giving the driver the worst ride in the vehicle compared to the rest of the crew. The vertical accelerations at the cg of the vehicle were measured but are not shown because they were not nearly as severe as the accelerations experienced by the driver. The minimum and maximum accelerations are reported for each run over each of the three RMS courses. The peak accelerations were quite similar for both vehicles at the more moderate speeds for each course. As the speed increased, the peak accelerations for the standard

Stryker became more severe in comparison to the peak accelerations for the MR Stryker.

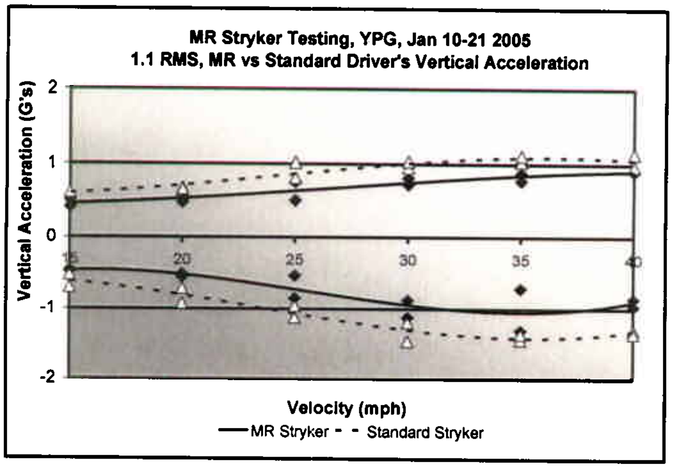


Figure 13 – Driver's Vertical Accelerations (1.1" RMS)

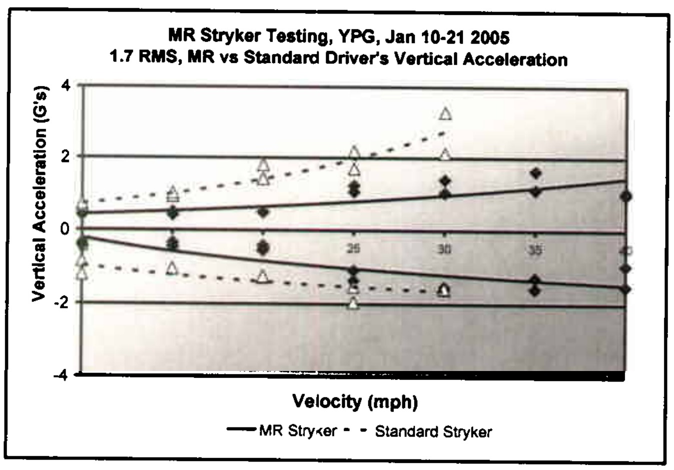


Figure 14 – – Driver's Vertical Acceleration (1.7" RMS)

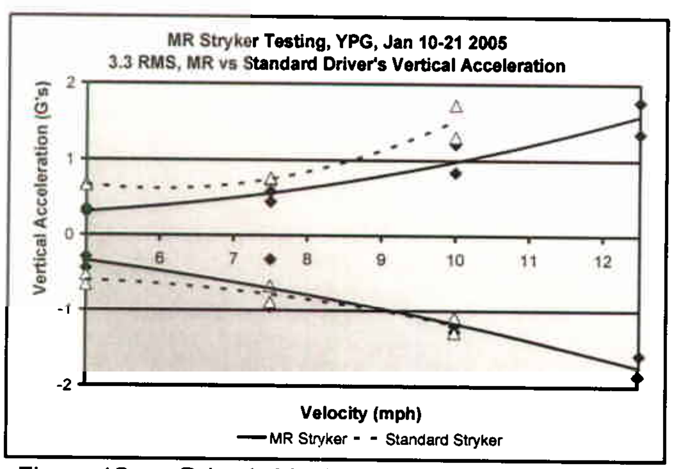


Figure 15 – – Driver's Vertical Acceleration (3.3" RMS)

Another measure of ride quality and platform stability over the RMS courses is depicted in Figures 16-18. Here the maximum chassis pitch rates for the MR Stryker and the standard Stryker are recorded for each RMS course. Even though the MR Stryker has a lower pitch rate on courses 3 and 5, the total pitch displacement is about the same for the two vehicles. (See Figures 16 and 18), The most drastic difference in pitch motion occurred during the run over the 1.7" rms course. (Figure 17) The MR Stryker had a pitch rate that was quite lower than that of the standard vehicle. The pitch rate of the standard vehicle is maximized between 15 and 20 mph because the course is at the natural frequency of the vehicle causing the worst possible ride for the standard Stryker.

Figure 16 illustrates results for the MR Stryker for runs 25, 30, and 40 mph. The data for runs 10, 15, and 20 mph was unacceptable because of bad data therefore, it is not presented in the graph.

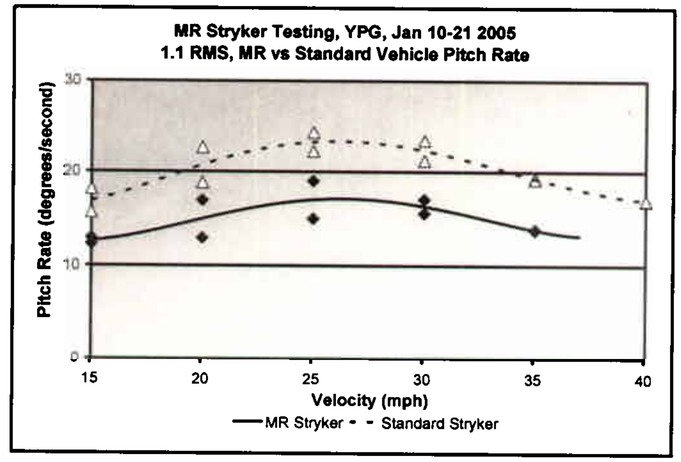


Figure 16 - Maximum Pitch Rates (1.1" RMS)

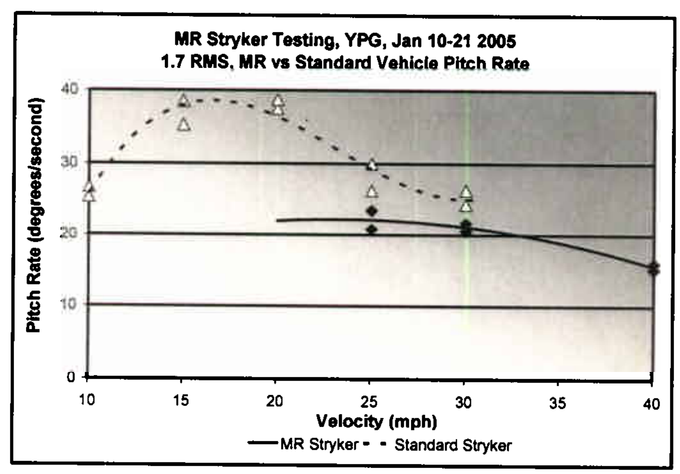


Figure 17 - Maximum Pitch Rates (1.7" RMS)

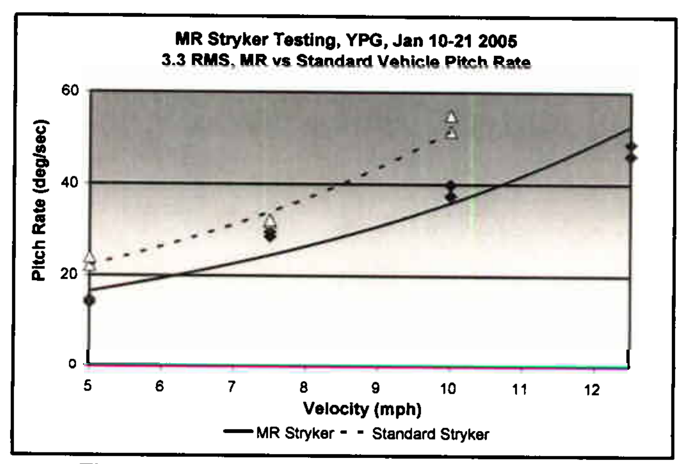


Figure 18 - Maximum Pitch Rates (3.3" RMS)

The ride quality of a vehicle is quantified in terms of the vehicle speeds over different RMS courses at which the vehicle's driver would experience 6 watts of vertical absorbed power. The driver's vertical absorbed power for each RMS course run was calculated and the results are plotted separately for the MR Stryker and the standard Stryker over each of the three RMS courses. These driver absorbed power plots are shown in Figures 19-21.

It is apparent that neither the MR Stryker nor the standard Stryker ever reached the 6 watt limit on the 1.1" rms course and the 3.3" rms course, however, the MR Stryker did endure about half the amount of vibration as the standard Stryker reaching respectively 2 watts and 4.5 watts. The vibration levels on the 3.3" rms course are very similar. This is do to the size and frequency of the bumps on the 3.3" rms course. The bumps are so large and spaced apart to the point were the vehicle is actually progressing over the bumps as a complete vehicle and not at each wheel separately.

The most drastic reduction in absorbed power is illustrated in Figure 20. The standard vehicle reaches the 6 watt limit at about 22 mph while the MR Stryker does not reach the 6 watt limit until about 38 mph. This is a 72% increase in cross-country speed.

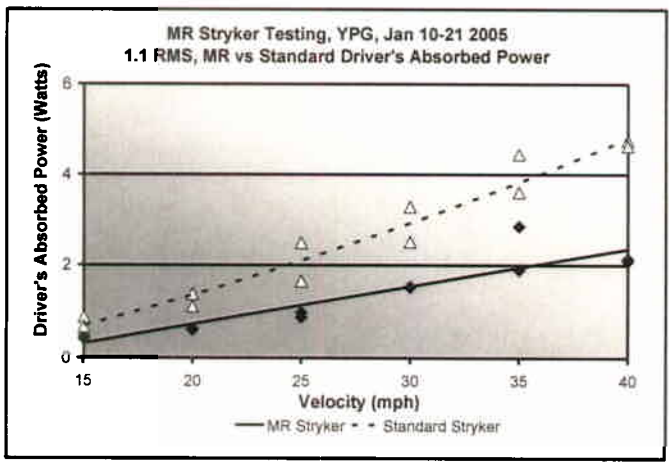

Figure 19 – Driver Absorbed Power 1.1" RMS

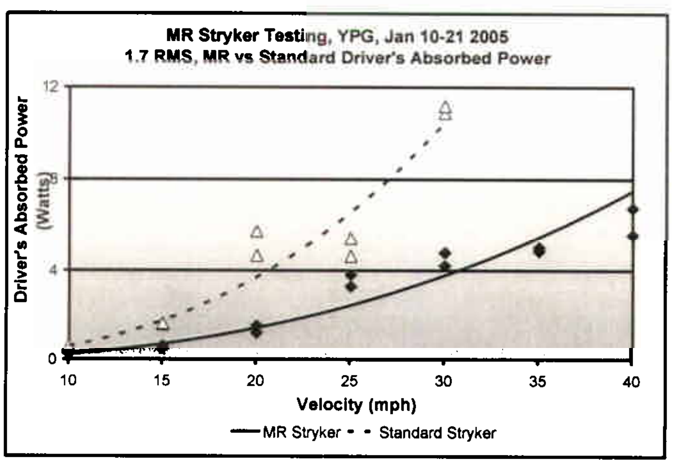

Figure 20 – Driver Absorbed Power 1.7" RMS

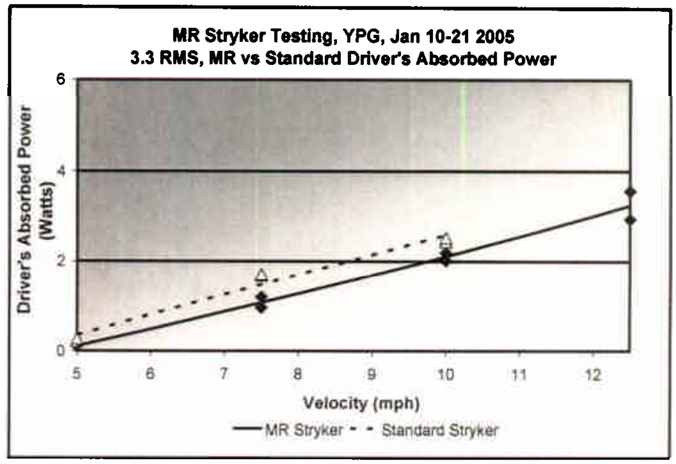

Figure 21 – Driver Absorbed Power 3.3" RMS

The resulting ride limiting speed curves for the MR Stryker and the standard Stryker are then shown in Figure 21. A fairly significant increase in ride limiting speed can be seen here for the MR Stryker over the standard Stryker for the 1.7" rms course. The 1.7" rms terrain yielded about a 50% improvement for the MR Stryker, whereas the 1.1" rms course and the 3.3" rms course showed a minimal difference in the ride limiting speed. Overall, there was improvement in cross-country speeds on all RMS courses.

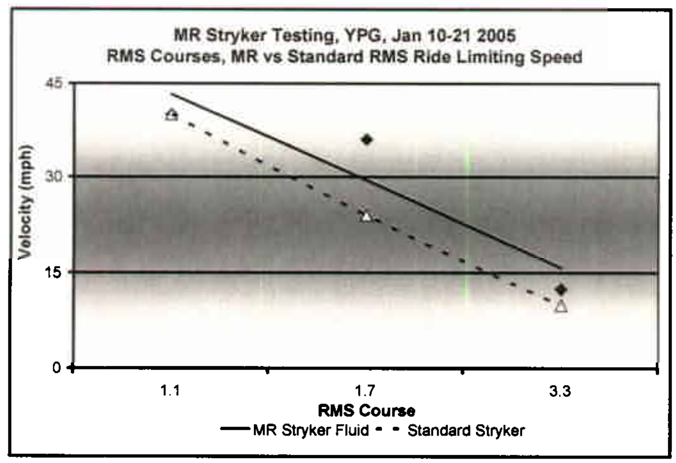

Figure 22 - Ride Limiting Speed

The increased wheel accelerations of the MR Stryker seem reasonable based on the increased wheel displacement of the vehicle. This is a result of the wheels being able to respond to the terrain using controlled variable damping. The increase in wheel displacement reduced the amount of chassis motion, thereby lowering the pitch rate and the amount of driver absorbed power.

## SHOCK PERFORMANCE

The shock testing is based on the driver's tolerance to a single vertical acceleration input. The limiting shock level of vertical acceleration for the driver is considered to be 2.5 g's. The vehicle was tested over 6, 8, 10, and 12 inch high half round obstacles. When measured, the actual height of each half round was found to be slightly higher than indicated. The obstacles were made by cutting steel pipe in half lengthwise, and welding the half-round obstacles to steel plates. The half-round

obstacles were bolted down on a concrete test area. Each obstacle was then negotiated at increasing speed until it was felt the shock was too severe to increase the speed further.

Figures 23-26 record the driver's vertical acceleration versus vehicle speed for each of the four obstacle heights. The driver's peak acceleration over the 6", 8", and 10" obstacles were greatly reduced for the MR Stryker compared to the standard Stryker. The driver's peak acceleration over the 12" obstacle was almost identical. This is expected because both vehicles are reaching their maximum wheel extensions at 12 inches.

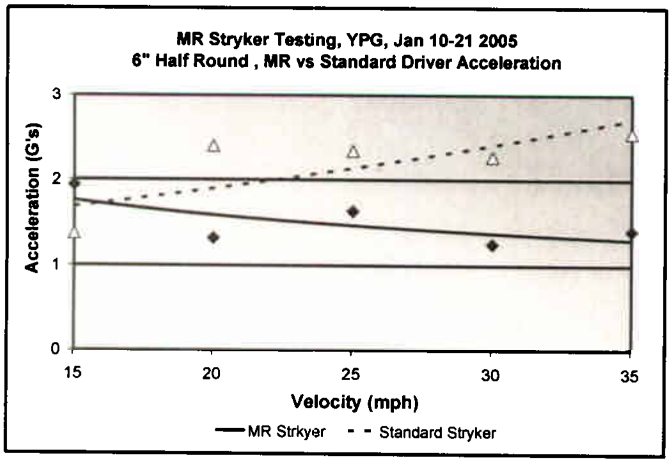


Figure 23 - 6" Bump Driver's Acceleration

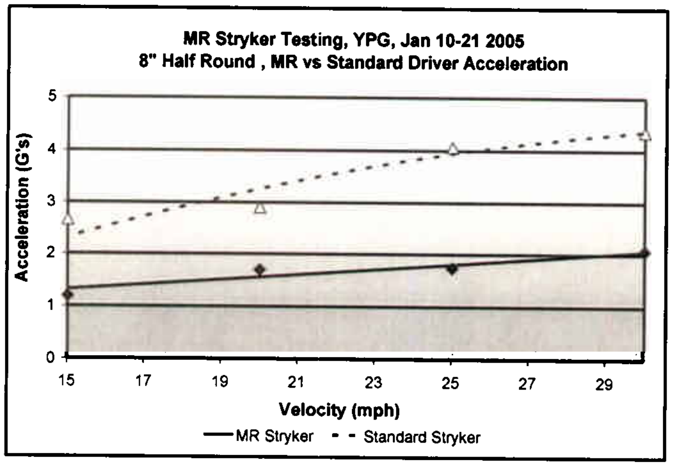


Figure 24 - 8" Bump Driver's Acceleration

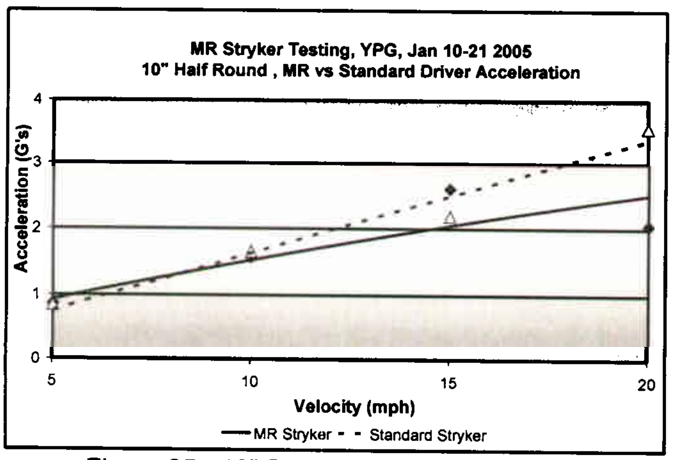


Figure 25 - 10" Bump Driver's Acceleration

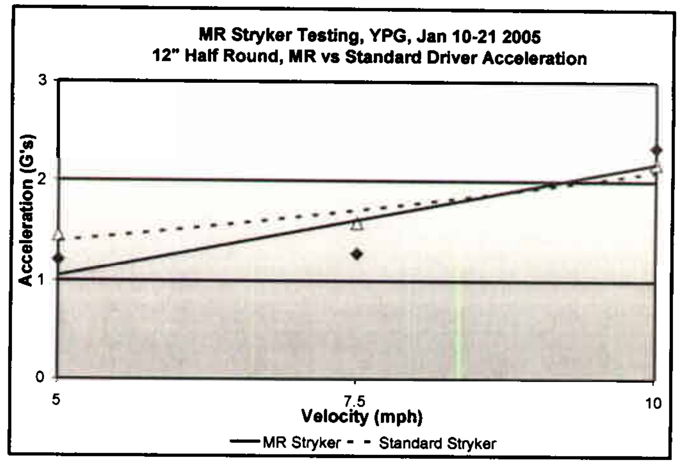


Figure 26 – 12" Bump Driver's Acceleration

The comparison of driver's peak acceleration over obstacles for the two vehicles is summarized in Figure 27. This comparison, it should be noted, is made at the 1.5 G vertical acceleration level. This was done because the test data shown never appreciably exceeded 2 Gs. The 1.5 G shock speed is significantly improved by almost 100% on the 8" bump, about 10% on the 10" bump, and about 15% over the 12" bump. The 1.5 G shook speed was about the same for the 6" bump.

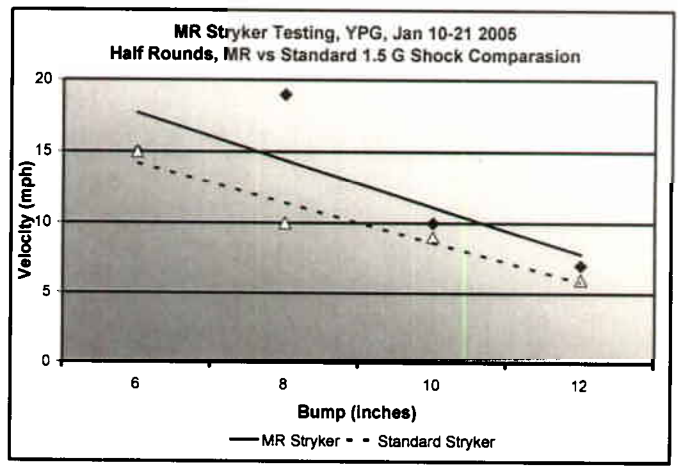


Figure 27 – 1.5 G Shock Comparison

## MANEUVERABILITY PERFORMANCE

The maneuverability of the MR Stryker and the standard Stryker was compared based on slalom and lane change maneuvers as described earlier. The signals of interest for these tests were taken to be the suspension travel at each wheel on the left side of the vehicle, the chassis lateral acceleration, the chassis roll rate, and the steering command angle. Since the lane change maneuver involves both a left and a right turn of approximately equal severity, only the suspension travel on the left side of the vehicle is considered. For most of these signals of interest, plots are included for the runs taken in the north and south directions for the MR Stryker and the standard Stryker. The wheel travel, however is reported as the total wheel travel used (as it was in the RMS course runs shown earlier), and the lateral acceleration is simply the largest magnitude of lateral acceleration experienced for each run.

## Lane Change Course

The total range of suspension travel used, as a function of vehicle speed for the MR Stryker and the standard Stryker is illustrated in figures 28-29. The wheel travel of the standard Stryker is significantly less in the rear of the vehicle than in the front of the vehicle. This is not true for the MR Stryker, the wheel travel is slightly less in the rear of the vehicle but only at higher speeds.

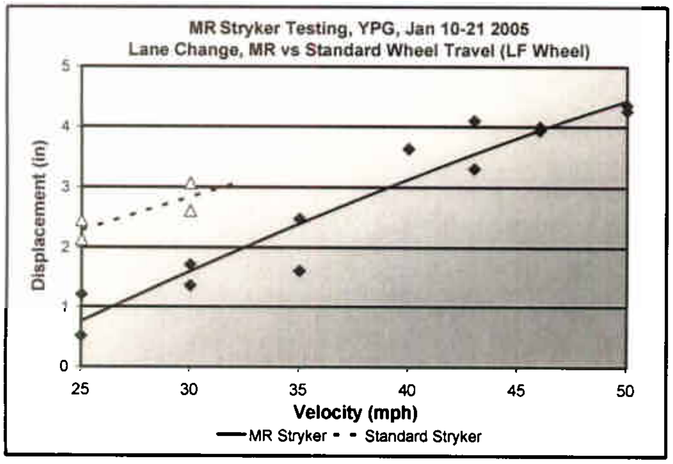


Figure 28 - Left Front Wheel Travel (Lane Change)

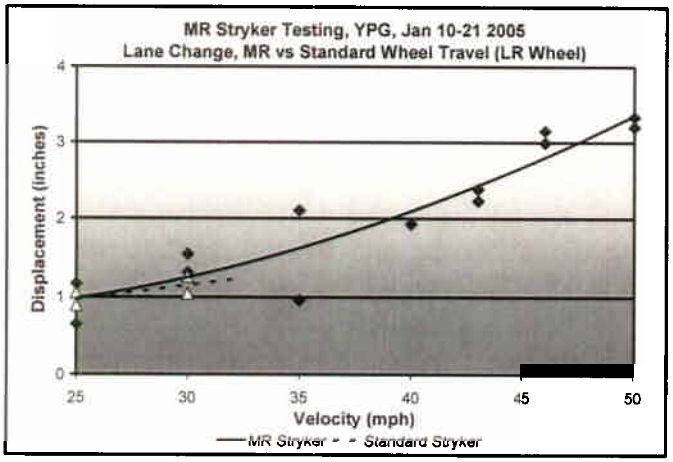


Figure 29 - Left Rear Wheel Travel (Lane Change)

The standard Stryker was able to run the lane change course without hitting any pylons up to 35 mph. The standard Stryker made six attempts at 40 mph, but was never able to make it through without hitting a pylon. The data for the 35 mph run was unacceptable, therefore the data for runs 25 mph and 30 mph are the only runs represented in Figures 27 and 28.

The MR Stryker was able to complete the lane change course without hitting any pylons up to 50 mph. The test driver wanted to attempt 55 mph, but the test director would not allow it do to safety regulations. This is a 43% improvement for on-road maneuverability performance.

The reduction in wheel travel directly correlates with the reduction in roll rate and steering angles illustrated in Figures 30 and 31.

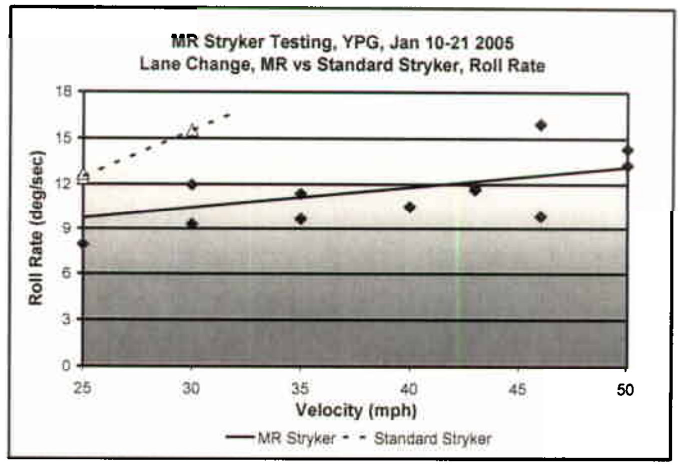


Figure 30 - Roll Rate (Lane Change)

Figures 30-31 record the minimum and maximum values for the steering command and the resulting vehicle roll rate for each test run. The MR Stryker has a reduced roll rate of 30%, there by reducing the steering angle by the equivalent.

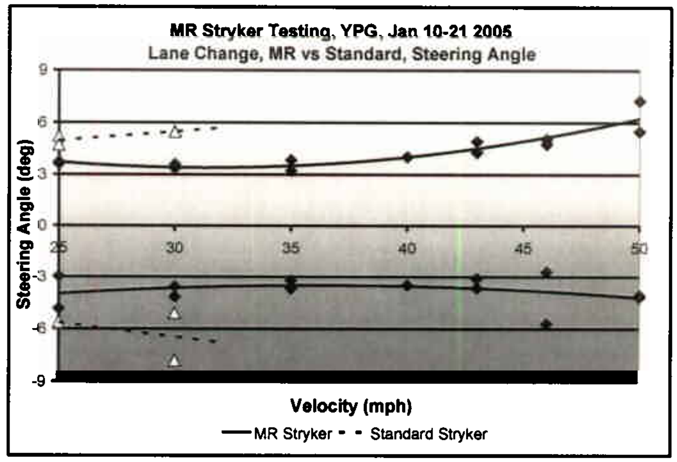


Figure 31 - Steering Angle (Lane Change)

The lateral acceleration of the active and passive systems is shown in Figure 32. Once again the MR Stryker performed better than the standard Stryker.

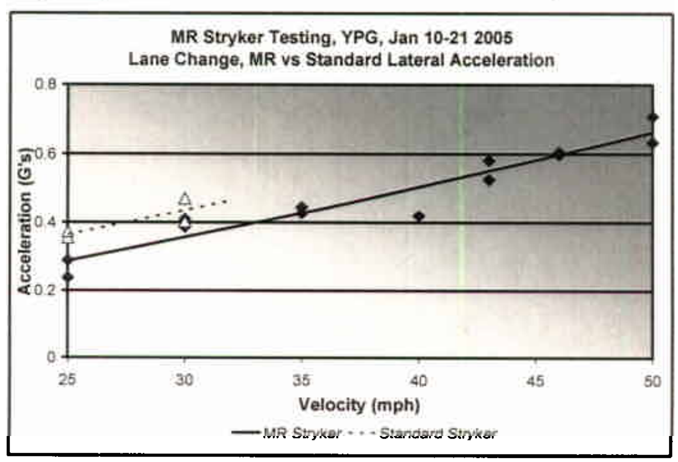


Figure 32 - CG Lateral Acceleration (Lane Change)

<u>Slalom Course</u>

The total range of wheel travel used, as a function of vehicle speed for the MR Stryker and the standard Stryker is illustrated in figures 33-34.

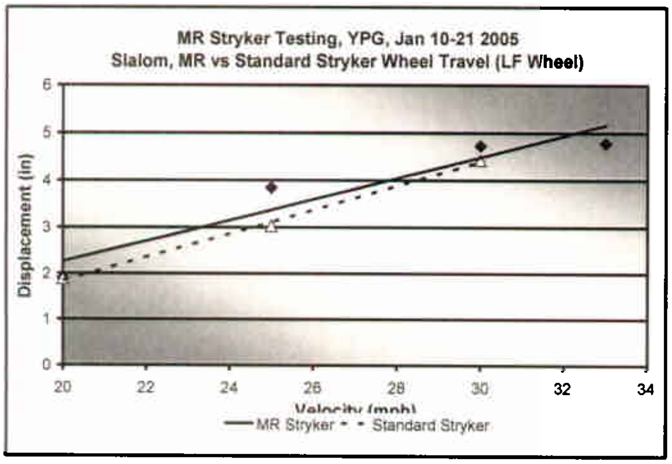


Figure 33 - Left Front Wheel Travel (Slalom)

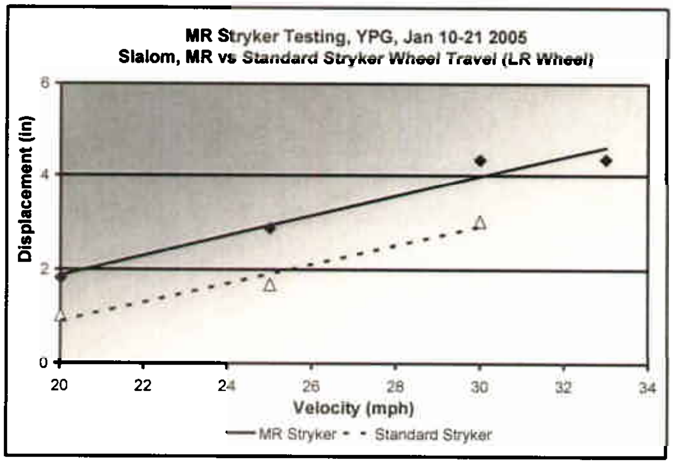


Figure 34 - Left Rear Wheel Travel (Slalom)

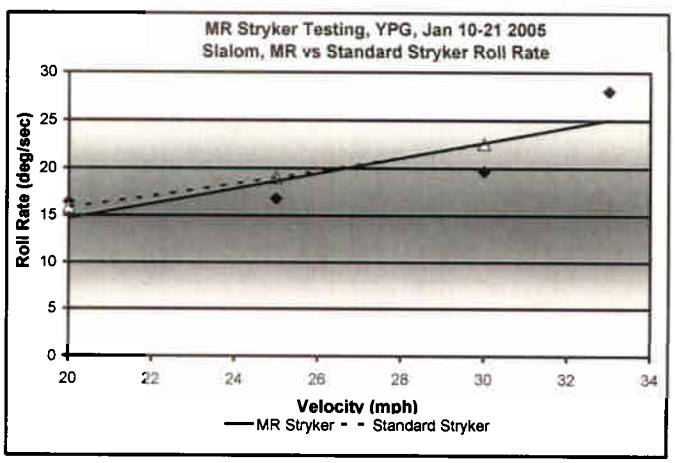


Figure 35 - Roll Rate (Slalom)

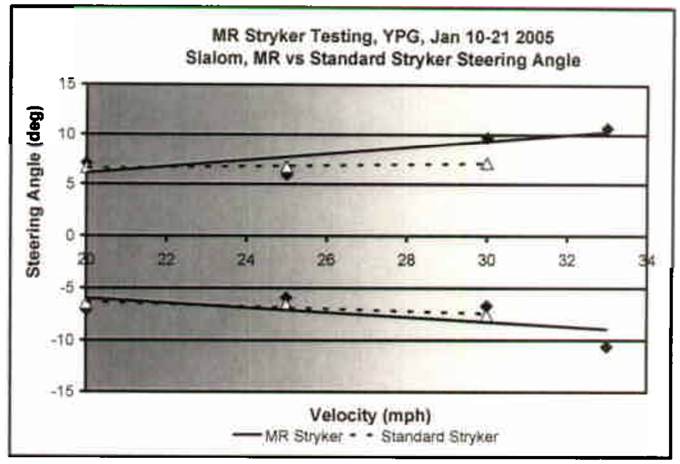


Figure 36 - Steering Angle (Slalom)

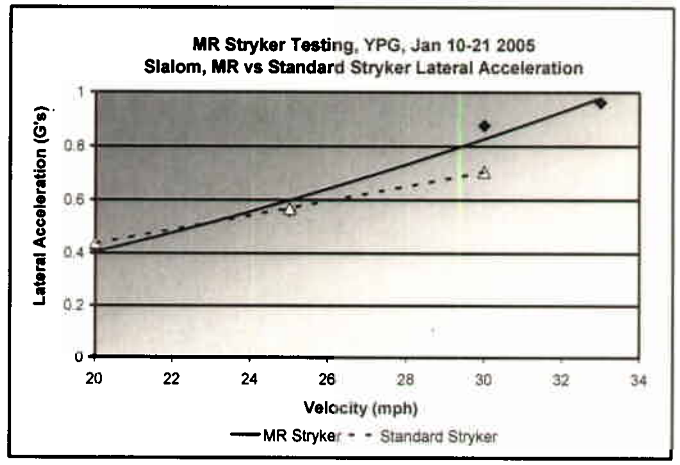


Figure 37 - Lateral Acceleration (Slalom)

The wheel travel of the standard Stryker is slightly less that of the MR Stryker for the front wheel, but is significantly less for the rear wheel. An interesting observation is that the wheel motion for the MR Stryker is almost identical for both the front and rear wheels. The difference in roll rate between the standard Stryker and MR Stryker are negligible as illustrated in figure 35. The steering angle, illustrated in figure 36, is slightly greater for the MR Stryker, which is reasonable based on the greater wheel displacement. As illustrated in figure 37, the accelerations at the lower speeds seem to be identical, but tend to vary more as the speed increases.

The standard Stryker maneuvered through the course at 20, 25, and 28 mph. One attempt was made at 30 mph, but the contacted 2 pylons making the data unacceptable. The MR Stryker completed runs through the course at 20, 25, 30, and 33 mph.

The comparison of the data for the slalom test does not demonstrate a drastic improvement as was noted during the lane change test. However, the MR Stryker was able to transverse the course 5 mph faster than the standard vehicle. This does demonstrate some improvement.

## CONCLUSION

The performance of the MR Stryker with the semiactive MR fluid suspension was quite impressive overall. The MR fluid suspension showed improvements in ride quality, shock performance, maneuverability, and roll stability.

The MR Stryker showed an increase in cross-country speeds during the ride quality testing up to 72%. This was demonstrated on RMS course 4 at approximately 20 mph in the standard vehicle versus 38 mph in the MR Stryker. The MR Stryker also demonstrated a reduction in vehicle vibrations as well as a reduction in pitch motion. This was demonstrated throughout the RMS course testing and the half round bump testing.

The results of the maneuverability testing are also impressive. The MR Stryker showed an increase in speed during the lane change test from 38 mph to over 50 mph. This improvement was possible due to the reduction in roll rate of up to 30%.

The magneto-rheological fluid semiactive suspension system has demonstrated significant improvements in ride quality and high speed maneuverability. This in turn could increase battlefield effectiveness, safety levels for the operator and crew and reducing potential for vehicle damage and associated maintenance activities. The overall conclusion is that the MR Stryker performance test was a success.


## ACKNOWLEDGEMENTS

The authors would like to thank all of those involved, especially Instrumentation, Data Collection, Video, and the Drivers from YPG


## CONTACT


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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

cg - Center of Gravity

excursion – the suspension displacement during a particular incident

MR – Magneto-Rheological Fluid Suspension

HMMWV - High Mobility Multi-purpose Wheeled Vehicle

ICV – Infantry Carrier Vehicle

MPH - Miles per hour

rms - Root Mean Square

SBIR – Small Business Innovative Research

TACOM - U.S. Army Tank-automotive and Armaments Command

TARDEC - U.S. Army Tank-Automotive Research, Development and Engineering Center

YPG - Yuma Proving Grounds

**APPENDIX A - SCOPE OF WORK**

Scope of Work

21 January 2005/MillenWorks Test

1 SCOPE. This Scope of Work (SOW) covers technical support and testing services to be provided to the Mobility Directorate of the U.S. Army Tank-automotive and Armaments Command (TACOM). This support encompasses technical work and the use of test facilities.

1.1 Background. TACOM is involved in the development of advanced suspension technology to increase the mobility performance of Army vehicles. The particular application of a magneto-rheological fluid semi-active suspension (MR) to achieve increased performance is being explored. Comparison testing between the MR fluid suspension and a passive system is being sought to quantify the actual performance gains for ride quality, shock, and maneuverability. The platform for this particular test is the Stryker ICV (Infantry Carrier Vehicle). One test period of one to two weeks is planned for running both the MR fluid suspension Stryker and the passive Stryker.

2 APPLICABLE DOCUMENTS.

2.1 Course Layouts. See Appendix A1.

2.2 Testing Procedures. See Appendix A2.

3 REQUIRMENTS.

3.1 General. Use of the test facilities shall include support of test personnel, preparation of test areas or courses in conjunction with tests requested, installation of data collection equipment and instrumentation, and production of test results in digital form on CD-ROM and video requested. TACOM will coordinate the overall test program with cooperation from Rod Millen Special Vehicles, and arrange delivery of the MR Stryker. Testing shall begin upon the arrival of the MR Stryker. All test results shall be delivered no later than 30 days after final testing is completed.

3.2 Instrumentation. The passive Stryker vehicle and the MR Stryker vehicle shall be instrumented with sensors mounted on solid non-resonating surfaces to measure the following at the specified location:

3.2.1.1 Vertical acceleration of each wheel on the left side of the vehicle (4 sensors)

3.2.1.2 Differential position of suspension or wheel travel for each wheel on the left side of the vehicle (4 sensors)

3.2.1.3 Tri-axial acceleration at CG (vertical, longitudinal, lateral) (1 sensor)

3.2.1.4 Tri-axial angular rate at CG (roll, pitch, yaw) (1 sensor)

3.2.1.5 Speed (longitudinal) (1 sensor)

3.2.1.6 Steering angle (1 sensor)

3.2.1.7 Vertical acceleration at driver's floor (1 sensor)

3.2.2 An Instrumentation Map shall be provided for each vehicle indicating sensor locations.

3.3 Test Descriptions.

3.3.1 Ride. Ride quality tests shall be conducted according to the test procedure described in the Appendix (A2). Each vehicle shall be driven over the following courses (approx. RMS) starting at 5 MPH in 5-MPH increments (refinement to 2.5 MPH increments may be needed for special cases):

3.3.1a Rolling Resistance. The Rolling Resistance or "Coast Down" test should be conducted according to the test procedure described in the Appendix (A2). Tests should be conducted on level, Course 3 (1.5" RMS), and Course 4 (2.0" RMS) from a range starting at 5 MPH and ending at 25 MPH.:

3.3.1.1 Course 3 - 1.1" RMS roughness

3.3.1.2 Course 4 – 1.7" RMS roughness

3.3.1.3 Course 5 - 3.3" RMS roughness

3.3.2 Shock. Shock level tests shall be conducted according to the test procedure described in the Appendix (A2). Each vehicle shall be driven over the following, full vehicle width, half-round bump heights starting at 5 MPH in 5-MPH increments (refinement to 2.5 MPH increments may be needed for special cases):

3.3.2.0 4" half-round

3.3.2.1 6" half-round

3.3.2.2 8" half-round

3.3.2.4 10" half-round

3.3.2.5 12" half-round

3.3.3 Maneuverability.

3.3.3.1 Double Lane Change. Double Lane Change tests shall be conducted according to the test procedure described in the Appendix (A2). (For the case of the Stryker, the vehicle length shall be 275 inches and the width shall be 107 inches). Each vehicle shall be driven over the course starting at 5 MPH in 5-MPH increments (refinement to 2.5 MPH increments may be needed for special cases).

3.3.3.2 Constant Step Slalom. Constant Step Slalom tests shall be conducted according to the test procedure described in the Appendix (A2). Each vehicle shall be driven over the course with the

following cone spacing starting at 5 MPH in 5-MPH increments (refinement to 2.5 MPH increments may be needed for special cases):

3.3.3.2.1 d = 30 m (98.4 ft)

3.4 <u>Data Acquisition.</u> All tests shall be run at the specified constant speeds or until deemed unsafe. A check of test data shall be made after each run and if any channel failure or dropout is present that test shall be rerun in entirety. The sample rate will be conducted at 500 Hz. All channel data for each test shall be stored and delivered on CD-ROM or Zip Disk format media in ASCII format (including file content description). Side and frontal video shots shall be taken of each test. A digital profile of all ride courses used shall be provided.

APPENDIX

A1 <u>COURSE LAYOUTS</u>

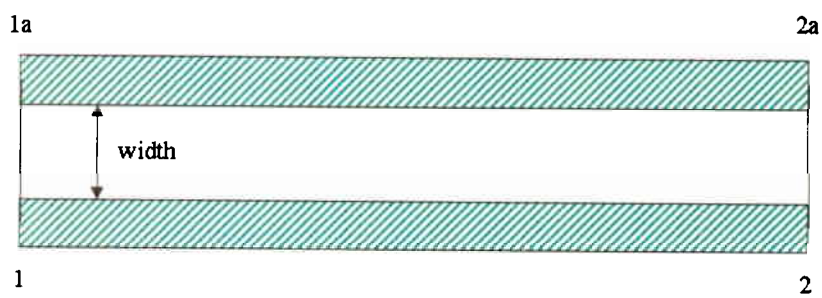


Figure A1 - Ride Course Layout

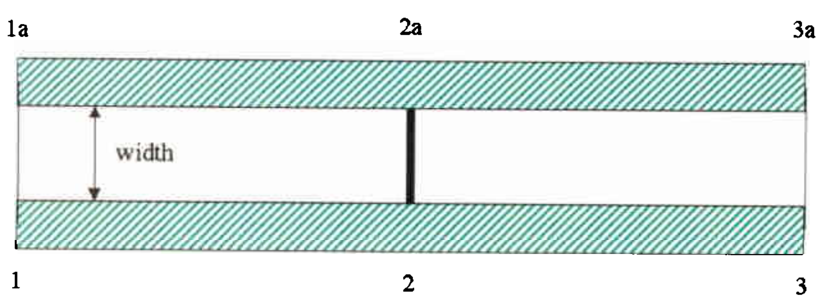


Figure A2 - Bump Course Layout

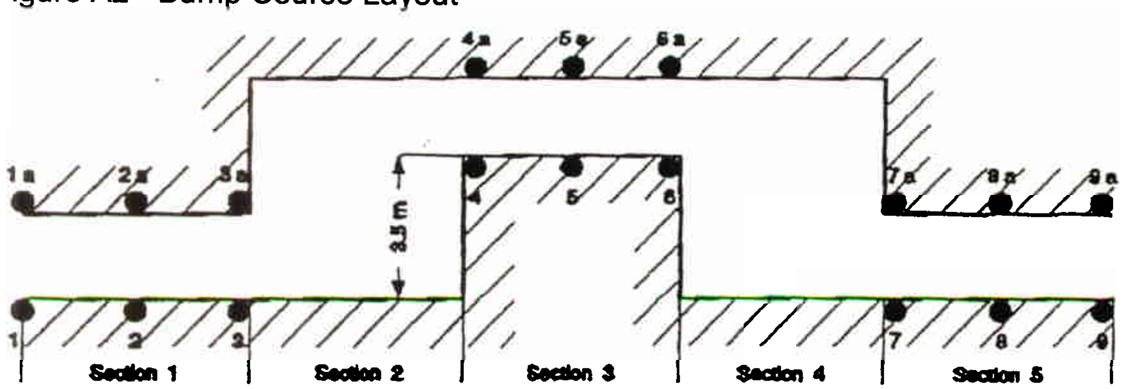

Figure A3 - Lane Change Layout

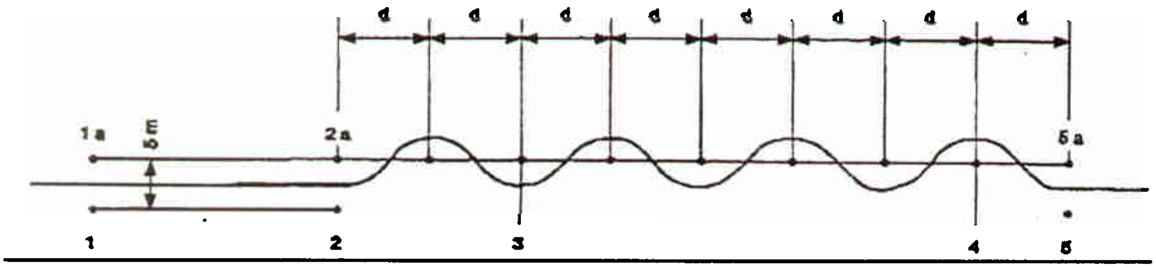


Figure A4 - Constant Step Slalom Layout

## A2 TEST PROCEDURES

### A2.1 Ride

A2.1.a Set up the course shown (Figure A1) with width at least two times the vehicle width and with distance (1-2) at least 150 m (492 ft).

A2.1.b Cross the line (1-1a) at the lowest vehicle speed laid down in the test plan and drive in a straight line through the section (1-2); attempt to continue through the remainder of the course while keeping the speed as steady as possible at this same value. Record parameters and note the vehicle behavior during the test.

A2.1.c Repeat (b) at the various speed increments laid down in test plan until: 1) maximum speed laid down in the test plan is reached or 2) it becomes impossible to cross the test area without staying on the course or 3) a speed is reached at which there is a risk of the vehicle falling onto its side, whichever occurs first.

A2.1.d Repeat the above procedure (a) to (c), but with the courses roughness as laid down in the test plan.

### A2.2 Shock

A2.2.a Set up the course shown (Figure A2) with width at least two times the vehicle width including a full vehicle width half-round bump at (2-2a).

A2.2.b Cross the line (1-1a) at the lowest vehicle speed laid down in the test plan and drive in a straight line through the section (1-3); attempt to continue through the remainder of the course whilst keeping the speed as steady as possible at this same value. Record parameters and note the vehicle behavior during the test.

A2.2.c Repeat (b) at the various speed increments laid down in test plan until: 1) maximum speed laid down in the test plan is reached or 2) it becomes impossible to cross the test area without staying on the course or 3) a speed is reached at which there is a risk of the vehicle falling onto its side, whichever occurs first.

A2.2.d Repeat the above procedure (a) to (c), but with the half-round bump height as laid down in the test plan.

A3.3 Maneuverability

A3.3.1 Double Lane Change

A3.3.1.a Set up the course shown (Figure A3) with the following dimensions:

Section 1:Length = 15 m (49.2 ft)
Width = 1.1 * vehicle width + 0.25 m (0.82 ft)

Section 2:Length = vehicle length + 24 m (78.72 ft)
Width = 3.5 m (11.48 ft) + Section 3 width
Section 3 Length = 25 m (82 ft)
Width = 1.2 * vehicle width + 0.25m (0.82 ft)

Section 4:Length = vehicle length + 24 m (78.72 ft)
Width = 3.5 m (11.48 ft) + Section 3 width

Section 5:Length = 15 m (49.2 ft)
Width = 1.1 * vehicle width + 0.25 m (0.82 ft)

A3.3.1.b Cross the line (1-1a) with the lowest vehicle speed laid down in test plan and drive in a straight line through the first section (1-3); attempt to continue through the remainder of the course (3-9) whilst keeping the speed as steady as possible at this same value. Record parameters and note the vehicle behavior during the test.

A3.3.1.c Repeat (b) at the various speed increments laid down in the test plan until: 1) maximum speed laid down in the test plan is reached or 2) it becomes impossible to cross the test area without knocking the cones down or 3) a speed is reached at which there is a risk of the vehicle falling onto its side, whichever occurs first.

A3.3.2 Constant Step Slalom

A3.3.2.a Set up the course shown (Figure A4) with distance "d" as laid out in the test plan and with distances (1-1a, 2-2a, 5-5a) at 5 m (16.4 ft).

A3.3.2.b Cross the line (1-1a) at the lowest vehicle speed laid down in the test plan and drive in a straight line through the section (1-2); attempt to continue through the remainder of the course (2-5)) while keeping the speed as steady as possible at this same value. The time needed to cross the section (3-4) is to be measured. Record parameters and note the vehicle behavior during the test.

A3.3.2.c Repeat (b) at the various speed increments laid down in test plan until: 1) maximum speed laid down in the test plan is reached or 2) it becomes impossible to cross the test area without knocking the cones down or 3) a speed is reached at which there is a risk of the vehicle falling onto its side, whichever occurs first.

A3.3.2.d Repeat the above procedure (a) to (c), but with the distances "d" set in turn at 15, 20 and 30 m (49.2, 65.6, and 98.4 ft).

## APPENDIX B - TEST MATRIX

# MR Stryker Testing at YPG January 10, 2005

| | | | | |
|---|---|---|---|---|
| MR Stryker | Course 3 | 15 | N | Controller Tuning of MR vehicle |
| MR Stryker | Course 4 | 10 | S | |
| MR Stryker | Course 5 | 5 | N | |
| | | | | |
| Passive | Course 3 | 15 | N | Checking Data Acquisition |
| MR Stryker | Course 3 | 15 | N | |
| Passive | Course 4 | 10 | S | |
| MR Stryker | Course 4 | 10 | S | |
| Passive | Course 5 | 5 | N | |
| MR Stryker | Course 5 | 5 | N | |

| Vehicle | Course | Speed | Direction | Begin testing with films and Data Acquisition |
|---|---|---|---|---|
| 14 | 3 | 15 | N | Jerry driving ICV14 |
| 14 | 3 | 15 | S | Fred driving ICV234 |
| 234 | 3 | 15 | N | |
| 234 | 3 | 15 | S | |
| 14 | 3 | 20 | N | |
| 14 | 3 | 20 | S | |
| 234 | 3 | 20 | N | |
| 234 | 3 | 20 | S | |
| 14 | 3 | 25 | N | |
| 14 | 3 | 25 | S | |
| 234 | 3 | 25 | N | |
| 234 | 3 | 25 | S | |
| 14 | 3 | 30 | N | |
| 14 | 3 | 30 | S | |
| 234 | 3 | 30 | N | |
| 234 | 3 | 30 | S | |
| 14 | 3 | 35 | N | |
| 14 | 3 | 35 | S | |
| 234 | 3 | 35 | N | |
| 234 | 3 | 35 | S | |
| 14 | 3 | 40 | N | |
| 14 | 3 | 40 | S | |
| 234 | 3 | 40 | N | |
| 234 | 3 | 40 | S | |
| | | | | |
| 14 | 4 | 10 | N | Jerry Driving ICV14 |
| 14 | 4 | 10 | S | Greg Driving ICV234 |
| 234 | 4 | 10 | N | |
| 234 | 4 | 10 | S | |
| 14 | 4 | 15 | N | |
| 14 | 4 | 15 | S | |
| 234 | 4 | 15 | N | |
| 234 | 4 | 15 | S | |
| 14 | 4 | 20 | N | |
| 14 | 4 | 20 | S | |
| 234 | 4 | 20 | N | |
| 234 | 4 | 20 | S | |

# MR Stryker Testing at YPG January 10, 2005

| Vehicle | Course | Speed | Direction | |
|---|---|---|---|---|
| 14 | 4 | 25 | N | String pot sticking on 234 L2 |
| 14 | 4 | 25 | S | |

# MR Stryker Testing at YPG January 11, 2005

String pot had a pebble, working fine, need to reinstall
controller Problem - amplifier not working correctly
signal being sent is not signal received, need to look for problem
need to go over data to determine when commands went bad
Need to rerun course 4 and possibly part of course 3 once determine when controller went bad

| Vehicle | Course | Speed | Direction | |
|---|---|---|---|---|
| 14 | 3 | 40 | N | Jerry driving ICV14 |
| 14 | 3 | 40 | S | Fred driving ICV234 |
| 234 | 3 | 40 | N | |
| 234 | 3 | 40 | S | |

Controller is tripping off from heat sensors getting warm on R1 and R2 which are in the engine and exhaust bay. Reprogram for correct temperature setting which was supposed to be higher

| Vehicle | Course | Speed | Direction |
|---|---|---|---|
| 234 | 3 | 40 | N |
| 234 | 3 | 40 | S |
| 14 | 4 | 10 | N |
| 14 | 4 | 10 | S |
| 234 | 4 | 10 | N |
| 234 | 4 | 10 | S |
| 14 | 4 | 15 | N |
| 14 | 4 | 15 | S |
| 234 | 4 | 15 | N |
| 234 | 4 | 15 | S |
| 14 | 4 | 20 | N |
| 14 | 4 | 20 | S |
| 234 | 4 | 20 | N |
| 234 | 4 | 20 | S |
| 14 | 4 | 25 | N |
| 14 | 4 | 25 | S |
| 234 | 4 | 25 | N |
| 234 | 4 | 25 | S |
| 14 | 4 | 30 | N |
| 14 | 4 | 30 | S |
| 234 | 4 | 30 | N |
| 234 | 4 | 30 | S |
| 234 | 4 | 35 | N |
| 234 | 4 | 35 | S |
| 234 | 4 | 40 | N |
| 234 | 4 | 40 | S |

# MR Stryker Testing at YPG January 12, 2005

Need to rerun ICV 14 for last 4 runs, L1 string pot broke. No film
Gyro in ICV 14 is showing up as 5 degrees offset in all directions
will replace gyro with new one for lane change and slalom for tomorrow
need to rerun ICV 234, lost L2 string pot and lost video on last 2 runs

| Vehicle | Course | Speed | Direction | |
|---|---|---|---|---|
| 14 | 4 | 25 | N | Jerry driving ICV 14 |
| 14 | 4 | 25 | S | Fred driving ICV 234 |
| 14 | 4 | 30 | N | |
| 14 | 4 | 30 | S | |
| 234 | 4 | 40 | N | |
| 234 | 4 | 40 | S | |
| | | | | |
| 234 | 4 | 25 | N | Jerry driving ICV 234 |
| 234 | 4 | 30 | S | |

Jerry interviewed by Don

| | | | | |
|---|---|---|---|---|
| 14 | 4 | 25 | N | Fred driving ICV 14 |
| 14 | 4 | 25 | S | |

Fred interviewed by Don

| Vehicle | Course | Speed | Direction | |
|---|---|---|---|---|
| 14 | 5 | 5 | N | Jerry driving ICV 14 |
| 14 | 5 | 5 | S | Fred driving ICV 234 |
| 234 | 5 | 5 | N | |
| 234 | 5 | 5 | S | |
| 14 | 5 | 7.5 | N | |
| 14 | 5 | 7.5 | S | |
| 234 | 5 | 7.5 | N | |
| 234 | 5 | 7.5 | S | |
| 14 | 5 | 10 | N | |
| 14 | 5 | 10 | S | |
| 234 | 5 | 10 | N | |
| 234 | 5 | 10 | S | R1 sensor went down, swap with R3 |
| 234 | 5 | 12.5 | N | |
| 234 | 5 | 12.5 | S | |

Rolling Resistance

| Vehicle | Course | Speed | Direction |
|---|---|---|---|
| 234 | 3 | 15 | N |
| 234 | 3 | 20 | N |
| 234 | 3 | 25 | N |
| 234 | 4 | 10 | N |
| 234 | 4 | 15 | N |
| 234 | 4 | 20 | N |

# MR Stryker Testing at YPG January 12, 2005

| Vehicle | Course | Speed | Direction | |
|---|---|---|---|---|
| 234 | 4 | 25 | N | |
| 234 | 5 | 5 | N | |
| 234 | 5 | 10 | N | |
| 14 | 3 | 15 | N | |
| 14 | 3 | 20 | N | |
| 14 | 3 | 25 | N | |
| 14 | 4 | 10 | N | |
| 14 | 4 | 15 | N | |
| 14 | 4 | 20 | N | redo, went into wrong gear |
| 14 | 4 | 20 | N | |
| 14 | 4 | 25 | N | |
| 14 | 5 | 5 | N | |
| 14 | 5 | 10 | N | |

need to rerun 234 for two runs, forgot to turn on data switch

| | | | |
|---|---|---|---|
| 234 | 3 | 15 | N |
| 234 | 3 | 20 | N |

Camera Side shot runs

| | | | |
|---|---|---|---|
| 234 | 4 | 20 | N |
| 234 | 4 | 40 | N |
| 234 | 4 | 20 | S |
| 234 | 4 | 40 | S |

# MR Stryker Testing at YPG January 13, 2005

| Vehicle | Course | Speed | Direction | |
|---|---|---|---|---|
| 14 | lane change | 25 | N | Jerry driving ICV 14 |
| 234 | lane change | 25 | N | Greg driving ICV 234 |
| 14 | lane change | 25 | S | |
| 234 | lane change | 25 | S | |
| 14 | lane change | 30 | N | |
| 234 | lane change | 30 | N | |
| 14 | lane change | 30 | S | |
| 234 | lane change | 30 | S | |

data guys checking to make sure new gyro in ICV 14 is giving good data

| | | | | |
|---|---|---|---|---|
| 14 | lane change | 35 | N | |
| 234 | lane change | 35 | N | |
| 14 | lane change | 35 | S | hit cone 3 west |
| 234 | lane change | 35 | S | |
| 14 | lane change | 40 | N | hit cones 8 and 9 east |
| 234 | lane change | 40 | N | hit cones 8 and 9 east |
| 14 | lane change | 40 | S | hit cones 3, 8 and 9 east |
| 234 | lane change | 40 | S | |
| 14 | lane change | 40 | N | hit cone 9 east |
| 234 | lane change | 43 | N | |

# MR Stryker Testing at YPG January 13, 2005

| Vehicle | Course | Speed | Direction | |
|---|---|---|---|---|
| 14 | lane change | 40 | S | hit cone 3 west |
| 234 | lane change | 43 | S | |
| 14 | lane change | 40 | N | hit cone 6 east |
| 234 | lane change | 43 | N | hit cone 4 east |
| 14 | lane change | 40 | S | hit cones 3 and 7 west |
| 234 | lane change | 43 | S | |
| 234 | lane change | 46 | N | |
| 234 | lane change | 46 | S | |
| 234 | lane change | 50 | N | hit cone 8 east |
| 234 | lane change | 50 | S | |
| 234 | lane change | 50 | N | |
| | | | | |
| 14 | slalom | 20 | N | |
| 234 | slalom | 20 | N | entered wrong cone |
| 14 | slalom | 25 | N | |
| 234 | slalom | 20 | N | |
| 14 | slalom | 30 | N | |
| 234 | slalom | 25 | N | |
| 14 | slalom | 33 | N | |
| 234 | slalom | 30 | N | |
| 234 | slalom | 33 | N | |
| 234 | slalom | 35 | N | |

# MR Stryker Testing at YPG January 21, 2005

string encoder in R1 was bad when reviewing data for course 5, need to rerun

| Vehicle | Course | Speed | Direction | |
|---|---|---|---|---|
| 234 | 5 | 7.5 | N | Greg driving ICV 234 |
| 234 | 5 | 7.5 | S | |
| 234 | 5 | 10 | N | |
| 234 | 5 | 10 | S | |
| 234 | 5 | 12.5 | N | |
| 234 | 5 | 12.5 | S | |

| Vehicle | Bump | Speed | Direction | |
|---|---|---|---|---|
| 14 | 6 | 15 | N | Jerry driving ICV 14 |
| 234 | 6 | 15 | N | Greg driving ICV 234 |
| 14 | 6 | 20 | N | forgot to hit data switch |
| 234 | 6 | 20 | N | 6" = 6 7/8" |
| 14 | 6 | 20 | N | |
| 14 | 6 | 25 | N | |
| 234 | 6 | 25 | N | |
| 14 | 6 | 30 | N | |
| 234 | 6 | 30 | N | |
| 14 | 6 | 35 | N | |
| 234 | 6 | 35 | N | |
| 14 | 8 | 10 | N | Fred driving ICV 14 |

# MR Stryker Testing at YPG January 21, 2005

| Vehicle | Bump | Speed | Direction | |
|---|---|---|---|---|
| 234 | 8 | 10 | N | 8" = 8 3/8" |
| 14 | 8 | 15 | N | |
| 234 | 8 | 15 | N | |
| 14 | 8 | 20 | N | |
| 234 | 8 | 20 | N | |
| 14 | 8 | 25 | N | |
| 234 | 8 | 25 | N | |
| 14 | 8 | 30 | N | |
| 234 | 8 | 30 | N | |
| 14 | 10 | 5 | N | 10" = 10 1/4" |
| 234 | 10 | 5 | N | |
| 14 | 10 | 10 | N | |
| 234 | 10 | 10 | N | |
| 14 | 10 | 15 | N | |
| 234 | 10 | 15 | N | |
| 14 | 10 | 20 | N | |
| 234 | 10 | 20 | N | |
| 14 | 12 | 5 | N | 12" = 12 7/8" |
| 234 | 12 | 5 | N | |
| 14 | 12 | 7.5 | N | |
| 234 | 12 | 7.5 | N | |
| 14 | 12 | 10 | N | |
| 234 | 12 | 10 | N | |

## APPENDIX C - STRYKER CHANNEL LIST

### LOGGER A

| | Data Channel | Location |
|---|---|---|
| 1. | Spindle 1 Acceleration (50G) | Cemented block directly on spindle |
| | | Positive = Upward |
| 2. | Spindle 2 Acceleration (50G) | Cemented block directly on spindle |
| | | Positive = Upward |
| 3. | Spindle 3 Acceleration (50G) | Cemented block directly on spindle |
| | | Positive = Upward |
| 4. | Spindle 4 Acceleration (50G) | Cemented block directly on spindle |
| | | Positive = Upward |
| 5. | Road Speed | Signal from Contact 5th wheel |
| | | |
| 6. | BUS Speed | Signal from vehicle's 1708 BUS |
| | | |
| 7. | Strut 1 Displacement | 30" String Potentiometer inline w/ strut |
| | | Positive = Extension |
| 8. | Strut 2 Displacement | 30" String Potentiometer inline w/ strut |
| | | Positive = Extension |
| 9. | Strut 3 Displacement | 30" String Potentiometer inline w/ strut |
| | | Positive = Extension |
| 10. | Strut 4 Displacement | 30" String Potentiometer inline w/ strut |
| | | Positive = Extension |
| 11. | Steering Angle | 30" String Potentiometer on center link |
| ICV-14 -Positive = Right turn | | ICV-234 – Positive = Left Turn |
| 12. | Data Switch | |
| | | |
| 13. | Light Relay | Triggers data logger for calculations |
| | | |
| 14. | Speed In | Calculation for Lane Change Test |
| | | |
| 15. | Speed Out | Calculation for Lane Change Test |
| | | |
| 16. | Distance | Distance traveled through Course |
| | | |
| 17. | Elapse Time | Calculation for Lane Change Test |
| | | |

**LOGGER B**

| | Data Channel | Location |
|---|---|---|
| 1. | Longitudinal Acceleration (10G) | X on vehicle floor tri-ax |
| | | Positive = Forward |
| 2. | Lateral Acceleration (10G) | Y on vehicle floor tri-ax |
| | | Positive = Leftward |
| 3. | Vertical Acceleration (10G) | Z on vehicle floor tri-ax |
| | | Positive = Upward |
| 4. | Driver Acceleration (10G) | Z axis on driver's seat frame |
| | | Positive = Upward |
| 5. | Road Speed (MPH) | Signal from Contact 5th wheel |
| | | |
| 6. | Bus Speed (MPH) | Signal form vehicle's 1708 BUS |
| | | |
| 7. | Pitch Rate (DPS) | Crossbow Gyro |
| | | Positive = Nose down |
| 9. | Roll Rate (DPS) | Crossbow Gyro |
| | | Positive = Left |
| 10. | Yaw Rate (DPS) | Crossbow Gyro |
| | | Positive = Right |
| 11. | Data Switch | |
| | | |
| 13. | Optical Switch | Located at front of vehicle. |
| | | |

## APPENDIX D - STRYKER SENSOR INSTRUMENTATION POSITION LIST

### *ICV-234 AND ICV-14 MR SUSPENSION TEST SENSOR POSITIONS*

| Instrument | Location (inches) | | |
|---|---|---|---|
| | Lateral | Longitudinal | Vertical |
| #1 Hub Accelerometer | 35.50 | 0.00 | 28.50 |
| #2 Hub Accelerometer | 35.50 | 47.25 | 29.50 |
| #3 Hub Accelerometer | 35.00 | 106.00 | 24.50 |
| #4 Hub Accelerometer | 35.00 | 153.50 | 24.50 |
| Driver's Seat Accelerometer | 16.50 | 12.50 | 38.00 |
| Rate Gyroscope | 0.00 | 97.00 | 33.75 |
| CG Accelerometer | 0.00 | 91.50 | 33.25 |
| Location is from the center of the 1st axle (lateral/longitudinal) | | | |
| Lateral - positive is to the left side of vehicle | | | |
| Longitudinal - positive is to the rear of the 1st axle centerline | | | |
| Vertical - positive is above the ground | | | |

**Instruments used for test:**

| | |
|---|---|
| Suspension Acceleration - | Endevco **7290A-50** – 50 G Accelerometer |
| CG Triax Acceleration - | Endevco **7290A-10** – 10 G Accelerometers |
| Driver Seat Vertical Acceleration - | Endevco **7290A-10** – 10 G Accelerometer |
| Strut Displacement - | UniMeasure **PA-30-NJC** – 30-inch Position Transducer |
| Steering Angle - | UniMeasure **PA-30-NJC** – 30-inch Position Transducer |
| CG Pitch Roll and Yaw Rates - | Crossbow **VG600AA** Fiber Optic Gyro System (ICV-14) |
| | Crossbow **VG700AA** Fiber Optic Gyro System (ICV-234) |
| Vehicle Speed - | Contact 5th wheel - Lane Change and Constant Step Slalom |
| | 1708 Bus for RMS and Half Rounds |

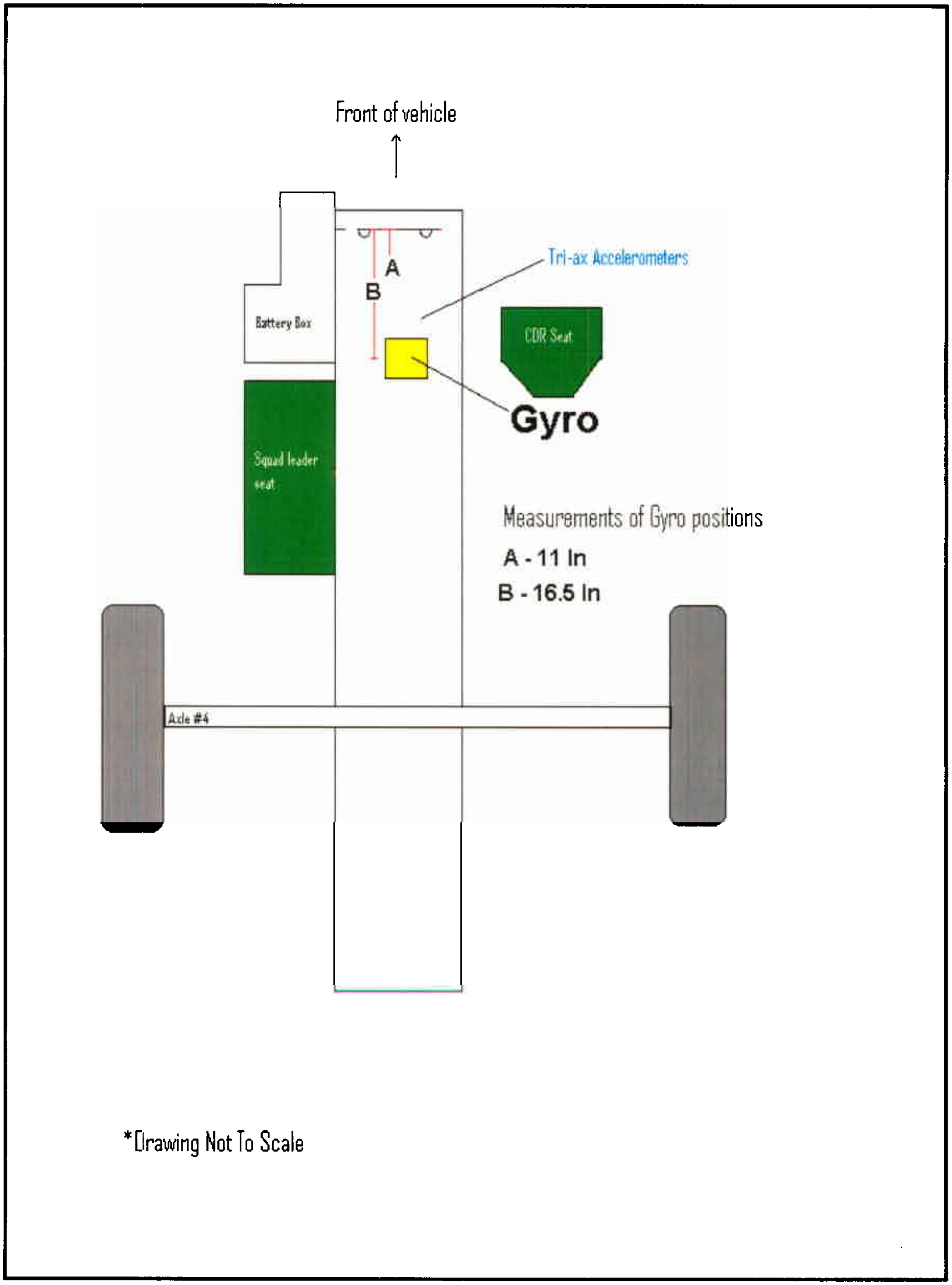


**Figure 38 - Stryker Instrumentation Diagram**